Reprinted from

GEOCHIMICA ET COSMOCHIMICA ACTA

Journal of the Geochemical Society

PERGAMON PRESS

OXFORD • LONDON • NEW YORK • PARIS

Geochimica et Cosmochimica Acta 1964, Vol. 28, pp. 793 to 806. Pergamon Press Ltd. Printed in Northern Ireland

A report on some recent major element analyses of tektites

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Abstract—Forty-two tektites and two "amerikanites" were partially or completely analysed for major elements. Included were 7 moldavites, 1 bediasite, 2 javanites, 15 philippinites, 12 indochinites and 5 australites. Many chemical similarities are noted between the philippinites and indochinites, but the two groups appear different in SiO_2, Al_2O_3, TiO_2 and, in particular, CaO contents. No decrease in alkali element content is observed from Indo-China to the Philippine Islands (i.e. west to east) as is observed across Australia. Selective volatilization cannot account for the differences in the two groups. Perhaps the higher CaO and Sr contents of the philippinites are due to contamination of the parent material by limestone. The CaO contents of the indochinites analysed are distinctly lower, and the MgO contents higher, than the analyses reported in BARNES (1940). Real variations, up to approximately 10 per cent for some constituents, exist within the philippinites and indochinites, and even within tektites from restricted sites. Tektites from two sites in the Philippine Islands are identical, within experimental error, in mean composition. The unity of chemical character of the australites and the southeast Asian tektites strongly suggest that they represent one large strewn field. New moldavite analyses do not indicate any systematic chemical variation across the Czechoslovakian strewn field.

Author

INTRODUCTION

THE purpose of this paper is to report some major element analyses of tektites that have been obtained in the rapid silicate analysis laboratory at the Massachusetts Institute of Technology. When we decided in 1959 to start a study of tektites it was apparent that more chemical data was necessary. From the published analyses it could be seen that the tektites from a given locality are quite similar in chemical composition and that there is some similarity between the different groups of tektites. However, it was difficult, if not impossible, to define the limits of variability among the several groups of tektites from the published analyses, as each analyst worked on only a few specimens, and undoubtedly different methods of chemical analysis were used by the various analysts. Also, many areas were poorly sampled; for example, only four philippinites were listed in BARNES' (1940) compilation of analyses.

Therefore, it seemed desirable to analyse a representative number of tektites from several different localities by uniform methods of analysis, making use of reliable rock standards to monitor the accuracy of the work. From such a study it should be possible to define the limits of variation in the chemical composition of tektites both within a group and between groups. As TAYLOR (1960, p. 85) states, "Uniformity of composition for groups of tektites, if established, would have far-reaching implications." Certainly, if, in addition to their peculiar composition,

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widely separated localities had essentially the same composition, it would be difficult to postulate any terrestrial origin.

Unfortunately, due to the scarcity of tektites in this country prior to the last several years, we could obtain only a limited number of tektites for destructive analysis. An adequate number of samples could be obtained from only the tektite rich areas of Indo-China and the Philippine Islands, and even here a larger collection from which to pick samples for analysis would have been desirable. The work of TAYLOR (1962) on the australites and CHAO (1963) on the bediasites have recently supplied extensive data in these fields.

ANALYTICAL TECHNIQUES

Most of the analyses reported in this paper were made by "rapid silicate" procedures. A large number of anomalous Al_2O_3 results were obtained using this method so it seemed desirable to determine this constituent by some other means. It was found that aluminum, as well as silica under certain conditions, could be determined by X-ray fluorescence techniques with no loss in accuracy and considerable improvement in precision (in the case of aluminum) over the rapid silicate method.

Rapid silicate procedures

The rapid silicate procedures used in this investigation were exactly as described by SHAPIRO and BRANNOCK (1956) except for CaO, MgO and FeO.

The automatic photometric titration procedure, employing a spectrophotometer and recorder, as described by SHAPIRO and BRANNOCK, was used in the determination of CaO and MgO. However, they have since modified the chemical procedures, eliminating the separation of iron and aluminum necessary under the system described in their paper, and they have supplied the M.I.T. rapid silicate laboratory with the necessary details. In the modified procedure iron and aluminum are complexed with a mixture of sodium cyanide and triethanolamine, and do not interfere with the calcium and magnesium titrations by Versene. Calcium is titrated at a pH between 12 and 12·7, using murexide as an indicator. (CaO + MgO) as MgO is titrated with Versene at a pH of approximately 9·5 using Eriochrome Black T as an indicator. The result obtained for CaO (changed to the corresponding amount of MgO) is subtracted from the result for (CaO + MgO) as MgO to obtain the amount of MgO. Thus the accuracy of the MgO determination is dependent upon the accuracy of the CaO determination. The standard used for both the CaO and (CaO + MgO) as MgO analyses is the National Bureau of Standard dolomite No. 88.

FeO was determined in most samples by the spectrophotometric method of SHAPIRO (1960) rather than the chemical dichromate titration procedure described by SHAPIRO and BRANNOCK (1956). Results obtained by the two methods on the same samples were in good agreement (SCHNETZLER, 1961, Table 14).

H_2O was not determined in the tektites as FRIEDMAN (1958) showed their water content to be extremely low (approximately 3 to 100 ppm), far below the detectable limit of the Penfield method.

Sample solutions were made in duplicate from two separate portions of the powdered tektite. In the SiO_2, Al_2O_3, total iron, CaO, (CaO + MgO), Na_2O and

K_2O determinations duplicate portions of each solution were analysed, making a total of four aliquots of each sample. Four spectrophotometer readings were made on each aliquot in the SiO_2, Al_2O_3, and total iron determinations, while an average of four flame photometer readings were made for each Na_2O and K_2O determinations. Thus the SiO_2, Al_2O_3, total iron, Na_2O and K_2O determinations were made from 16 instrument readings in total. One titration of CaO and (CaO + MgO) was made from each aliquot, making a total of four for each sample. The MnO and TiO_2 determinations were made from only one aliquot of each sample solution, as the precision was sufficiently high in these procedures to allow fewer replicate determinations. Four spectrophotometric readings were made of each aliquot in the MnO determinations and two spectrophotometer readings were made of each aliquot in the TiO_2 determinations. P_2O_5 was determined from two aliquots of each weighing but this element proved to be so low in tektites that the method was unreliable, and in the majority of samples it was not determined. FeO was determined by titration or photometrically on two separate weighings of the sample. In the photometric determinations two instrument readings were made in each determination.

The above scheme was followed in most analyses. Occasionally, however, the lack of sufficient sample necessitated the determination from only one weighing, or if duplicate weighings were made they were diluted to smaller volumes, so that fewer aliquots could be taken for some of the determinations. Also, when the precision appeared to be poor, the sample solutions were rerun, so some results are an average of a greater number of aliquot determinations than discussed in the scheme above.

Duplicate pairs from one weighing were usually analysed in one day and the duplicate pairs from the other weighing on another day. The samples to be analysed in any one day were chosen at random; therefore the tektites from any particular area were analysed at various times during the period of the investigation and not as a group.

X-ray fluorescence techniques

Chodos and Engel (1961) determined the total iron, CaO, MgO, K_2O, TiO_2 and MnO contents of amphibolite rocks by fluorescent X-ray spectrography and the results are in acceptable agreement with wet chemical analyses of the same samples. However, they found that the silica and aluminum results did not compare favorably with the wet chemical results, being accurate to only about 5 per cent of the amount present. They attributed this error to matrix effects, as their samples varied considerably in major element composition.

As the variation of the major elements in tektites is small, it was felt the matrix effects should be negligible in these samples. Since the aluminum determination is the least satisfactory of the rapid silicate procedures it was decided to attempt to analyse for this element by the X-ray fluorescence method and as the determination of silica by this procedure would eliminate one of the sample solutions in the rapid silicate procedure, this element was also attempted by the X-ray fluorescent method. It was believed this method might be successful in this investigation, while it had failed for Chodos and Engel (1961), for three reasons: (1) the matrix problem should be essentially non-existent, at least among the Australasian tektites, (2) the tektites, being a fairly homogeneous glass, would not exhibit the inhomogeneity of particle size and mineralogical composition that would be found in a powdered rock sample, and (3) the machine available allowed the rapid comparison of standard and sample, which was not the case in the machine used by CHODOS and ENGEL, thus reducing instrumental drift.

An attempt was first made to analyse powdered samples. The preparation and packing of the samples were essentially as described by CHODOS and ENGEL (1961). Agreement between the X-ray fluorescence and rapid silicate results were satisfactory for aluminum; the maximum difference between the two methods was about 2 per cent of the amount present, while the average difference was slightly less than $\pm 1\%$ (SCHNETZLER, 1961, Table 15).

The SiO_2 X-ray fluorescence results, however, were not satisfactory in the powdered samples. As silica is the predominant constituent in tektites relatively more precise values are desired than for the other constituents. A 1 or 2 per cent error is permissible in Al_2O_3, but not in SiO_2. There are several possible causes for the poor SiO_2 results on the powdered samples. Probably the greatest error is in the packing of the sample in the holder. CHODOS and ENGEL (1961) state that duplicate packings should agree within about 1 per cent. Duplicate packings in this investigation disagreed by as much as 2 per cent. Differences in grain size, resulting in differences in surface area exposed to the beam, might have been a minor factor. The sample holder wells might not have been uniform size—unfortunately this was not checked.

In view of this difficulty an attempt was made to analyse a cut surface of the solid tektite which was free of bubbles and which had been polished to eliminate any effect of surface irregularity. Using this procedure, triplicate results for SiO_2 were in agreement with the rapid silicate results to $\pm 0{\cdot}47$ per cent of the amount present, or better (SCHNETZLER, 1961, Table 15). Therefore it was concluded that the X-ray fluorescence SiO_2 and Al_2O_3 determinations on the solid samples and the Al_2O_3 determinations on the powdered samples were acceptable, and comparable to the rapid silicate determinations. However, the SiO_2 determinations on the powdered samples were not comparable to determinations by the rapid silicate procedure, and were not reported

The X-ray fluorescent unit used was a North American Phillips instrument with a tungsten target tube. The operating conditions were: EDDT crystal; pulse height analyser base $= 1{\cdot}50$, window $= 6$, flow proportional counter $= 1650$. Number of counts for powder: SiKα peak 51,200, background 800; AlKα peak 8000, background 800. Number of counts for solid: SiKα peak 102,400, background 800; AlKα 25,600, background 800.

The standards used were selected tektites which had been analysed for silica and aluminum by rapid silicate procedures.

Precision and accuracy

MERCY (1956) presents an extensive discussion on the precision and accuracy of the rapid silicate method of analysis. A good estimate of the precision of this work can be obtained as each sample was analysed in replicate and the rock standards G-1 and W-1 were repeatedly analysed during the course of the investigation. The results have approximately the following precision (expressed as the relative deviation of a single analysis): $SiO_2 \pm 0{\cdot}5\%$; Total Fe, photometrically determined

FeO, MgO, and $Na_2O \pm 2\%$; Al_2O_3, TiO_2, CaO and $K_2O \pm 3\%$; MnO $\pm 4\%$. The X-ray fluorescence results have a precision of approximately: $SiO_2 \pm 0{\cdot}8\%$; $Al_2O_3 \pm 2\%$. These values agree in general with estimates of precision given by MERCY (1956, p. 168).

The results of replicate analyses of G-1 and W-1 are given in Table 1. Most of these results are the average of determinations made on several different weighings.

Table 1. Analyses of G-1 and W-1

	G-1		W-1	
	This work	Accepted value	This work	Accepted value
SiO_2	72·57 (2)	72·35	53·09 (14)	52·40
Al_2O_3	14·12 (9)	14·32	15·02 (5)	15·11
Total Fe	1·98 (14)	2·04	11·09 (8)	11·22
FeO	0·91 (1)	0·98	8·55 (2)	8·63
MgO	0·38 (10)	0·40	6·68 (4)	6·58
CaO	1·23 (14)	1·40	10·81 (7)	10·97
Na_2O	3·45 (16)	3·31	2·25 (20)	2·07
K_2O	5·44 (6)	5·42	0·77 (9)	0·67
TiO_2	0·22 (5)	0·26	1·08 (11)	1·07
MnO	0·03 (6)	0·03	0·17 (8)	0·17
P_2O_5	0·07 (8)	0·10	0·13 (8)	0·15
Total	99·39	99·52	100·14	99·44

The numbers of analyses are given in parentheses. The accepted values listed are from STEVENS *et al.* (1960, p. 32). The only values that lie outside the "acceptable range", as defined by Stevens are SiO_2 in W-1 and CaO in G-1. The SiO_2 values in W-1 were determined during preliminary stages of the analytical period, using National Bureau of Standards feldspar #99 as standard. Perhaps the poor accuracy was due to the extreme difference in matrices. During the tektite analyses G-1 was used as standard, as its SiO_2 content is well known and its composition is similar to tektites, while NBS #99 was used to monitor the results. These analyses gave acceptable values for SiO_2 in the NBS feldspar. The CaO values for G-1 were consistently low in four different weighings of the sample; no explanation could be found. However, the CaO values for W-1 are satisfactory. The high results for Na_2O in both G-1 and W-1 (although they are both within the "acceptable range") are in excellent agreement with other flame photometric determinations as listed by STEVENS *et al.*(1960, p. 36).

As most of the analytical procedures used are independent of each other a total of the constituents close to 100 per cent is much more indicative of accuracy than in conventional methods of analysis where a constituent may be incompletely precipitated at one point and later precipitated with another constituent, and still give a good summation. It can be seen in Table 2 that the analyses total close to 100 per cent.

RESULTS

The results of the chemical analyses are given in Table 2. Included are partial or complete analyses of 42 tektites and 2 "amerikanites". The total iron contents, denoted in the table as Fe°, the specific gravity, and specimen weight are also given.

The results obtained by X-ray fluorescence are designated by asterisks; all results not so designated were determined by rapid silicate techniques. The X-ray fluorescence results are the average of several independent measurements, usually three for SiO_2 and two for Al_2O_3. If both rapid silicate and X-ray fluorescence determinations were made on a sample, the rapid silicate results are given in Table 2.

The SiO_2 values given in parentheses were obtained by subtraction from 100 per cent.

There appears to be general agreement between the analyses in Table 2 and the analyses reported by BARNES (1940). The differences between the old and new data can be attributed in most cases to the small number of samples and the variation within a group. However, the MgO and CaO averages for the 12 indochinites reported in this paper are distinctly different from the averages of the 24 indochinites

Table 2. Major element analyses of tektites

Moldavites

Locality	Ratiborova Lhotka, Bohemia	Strpi, Bohemia	Radomilice, Bohemia	Kroclov, Bohemia	Koroseky, Bohemia	Nechov, Bohemia	Slavice, Moravia
Sample #	T4575	T4572	T4574	T4570	T4571	T4090	T4573
SiO_2	78·59	79·99	84·48	80·12	78·93	79·26	81·35
Al_2O_3	10·99	10·36	7·79	9·70	10·42	10·28	10·98
Fe_2O_3	0·10	0·10	0·21	0·14	0·27	0·49	0·28
FeO	1·75	1·52	0·98	1·49	1·56	1·34	1·55
MgO	2·38	1·75	1·72	1·91	1·88	2·19	1·23
CaO	2·85	2·17	1·90	2·47	2·36	2·67	0·95
Na_2O	0·47	0·42	0·20	0·46	0·51	0·40	0·59
K_2O	3·44	3·32	2·40	3·57	3·62	3·47	3·57
TiO_2	0·32	0·32	0·22	0·27	0·30	0·31	0·32
MnO	0·08	0·07	0·05	0·06	0·06	0·07	0·03
P_2O_5	0·03	0·03	0·01	0·04	0·03	—	0·01
Total	101·01	100·05	99·96	100·23	99·94	100·48	100·86
Fe°	1·43	1·25	0·91	1·26	1·40	1·38	1·41
Wt. (g)	5·1	4·2	6·2	5·1	2·7	4·5	5·5

Locality	"Amerikanites"		Bediasite	Javanites		Philippinites		
	Philippine Islands	Peru	Grimes, Co. Texas			Santa Mesa site		
Sample #	3967	3996	T4106	T4102	T4104	T3959	T3960	T3961
SiO_2	72·7	—	(77·80)	(72·39)	(68·30)	71·0	72·1	70·9
Al_2O_3	12·75	—	12·69*	11·15*	13·43*	13·90	12·50	13·64
Fe_2O_3	0·69	0·28	0·77	0·78	0·65	0·87	0·72	0·82
FeO	0·95	0·41	3·15	5·41	6·30	4·29	4·28	4·18
MgO	0·11	0·03	0·61	3·97	4·96	2·70	2·58	2·67
CaO	0·86	0·25	0·56	2·33	2·60	2·95	2·90	3·20
Na_2O	3·85	4·59	1·54	1·19	1·01	1·37	1·30	1·36
K_2O	5·18	3·69	2·10	2·02	1·91	2·37	2·36	2·31
TiO_2	0·06	0·04	0·74	0·64	0·72	0·78	0·78	0·79
MnO	0·05	0·06	0·04	0·12	0·12	0·09	0·09	0·08
Total	97·20	—	(100)	(100)	(100)	100·40	99·70	100·05
Fe°	1·22	0·52	2·99	4·75	4·34	3·95	3·83	3·82
S.G.	2·461	2·363	2·42	2·437	2·438	2·460	2·455	2·456
Wt. (g)	4·9	26·6	12·05	1·76	1·82	5·3	1·9	2·8

Table 2 *cont.*

Locality	Philippinites									
	Santa Mesa site			Pugad–Babuy site						
Sample #	T3962	T3964	T3965	T3379	T3765	T3978	T3979	T3981	T3983	T3984
SiO_2	70·2	(70·26)	68·9	71·8	(70·02)	70·13	70·5*	70·5	70·6*	71·1*
Al_2O_3	14·09	14·01*	15·23	13·34	14·11*	14·66	14·59*	13·48	13·82*	14·13*
Fe_2O_3	0·80	0·53	0·50	0·63	0·93	0·65	0·93	0·63	0·57	0·75
FeO	4·18	4·33	4·81	4·38	4·13	4·21	4·04	4·29	4·42	4·26
MgO	2·67	2·32	2·71	2·60	2·53	2·44	2·61	2·41	2·51	2·65
CaO	3·30	3·38	3·27	2·98	3·54	3·28	3·14	3·34	3·06	2·86
Na_2O	1·30	1·76	1·29	1·33	1·32	1·55	1·34	1·56	1·27	1·34
K_2O	2·31	2·56	2·46	2·35	2·51	2·56	2·40	2·56	2·35	2·35
TiO_2	0·83	0·76	0·85	0·77	0·79	0·80	0·78	0·78	0·84	0·80
MnO	0·10	0·09	0·08	0·08	0·12	0·10	0·09	0·10	0·10	0·10
Total	99·88	(100)	100·16	100·33	(100)	100·35	100·42	99·64	99·61	100·34
Fe°	3·80	3·74	4·09	3·85	3·85	3·72	3·78	3·78	3·83	3·83
S.G.	2·454	2·411	2·429	—	2·452	2·432	2·439	2·379	2·455	2·456
Wt. (g)	4·1	4·5	5·7	—	203·5	13·9	10·3	7·9	9·8	22·8

Locality	Philippinites		Indochinites								
	Busuanga Island		Kouang–Tcheon–Wan			North Cambodia			Annam		
Sample #	T3985	T3986	T3987	T3988	T3989	T3990	T3991	T3992	T3993	T3994	T3995
SiO_2	72·1	71·0*	(72·98)	73·3*	71·33*	71·8*	73·7*	77·5*	72·9	72·0	71·2
Al_2O_3	12·96	13·56*	12·65	12·39*	13·68*	13·56*	13·32	11·59	12·96	13·02	12·28
Fe_2O_3	0·71	0·50	0·68	0·54	0·47	0·70	0·82	0·82	0·50	0·68	0·72
FeO	4·30	4·38	4·22	4·16	4·86	4·82	3·77	3·25	4·88	4·65	4·70
MgO	2·93	2·66	2·45	2·34	2·93	2·85	1·90	1·62	2·74	2·67	2·96
CaO	2·50	2·64	2·06	2·04	1·94	1·86	1·86	1·57	1·83	1·94	1·93
Na_2O	1·18	1·39	1·58	1·53	1·37	1·43	1·45	1·06	1·33	1·45	1·54
K_2O	2·17	2·40	2·49	2·46	2·34	2·49	2·62	2·10	2·27	2·32	2·38
TiO_2	0·75	0·76	0·72	0·77	0·74	0·81	0·75	0·66	0·74	0·73	0·74
MnO	0·09	0·10	0·10	0·10	0·09	0·11	0·09	0·08	0·11	0·09	0·09
Total	99·78	99·39	(100)	99·63	99·73	100·43	100·28	100·25	100·26	99·55	98·54
Fe°	3·84	3·75	3·75	3·61	4·10	4·22	3·50	3·10	4·15	4·09	4·15
S.G.	2·445	2·437	2·435	2·425	2·445	2·446	—	—	2·448	2·439	2·447
Wt. (g)	3·4	18·3	12·1	10·6	25·9	24·5	19·1	—	11·5	9·7	7·6

Locality	Indochinites			Australites				
	Dalat, S. Viet-Nam			?	Nullarbor Plain			Charlotte Waters
Sample #	T4218	T4219	T4220	T3310	T4214	T4215	T4216	T3313
SiO_2	(72·64)	(73·08)	(73·30)	(70·59)	(71·41)	69·0*	(70·96)	—
Al_2O_3	13·40*	12·38*	12·76*	13·21*	13·82*	15·32*	13·48*	—
Fe_2O_3	0·58	0·76	0·37	0·66	0·88	0·38	0·71	0·63
FeO	4·21	4·50	4·41	3·89	3·80	4·49	4·13	3·43
MgO	2·25	2·80	2·28	2·04	2·43	2·28	2·13	1·64
CaO	2·03	1·88	2·04	5·10	3·59	3·17	3·47	2·15
Na_2O	1·54	1·55	1·56	1·28	1·12	1·56	1·84	1·33
K_2O	2·50	2·32	2·50	2·39	2·07	2·50	2·61	2·38
TiO_2	0·76	0·63	0·70	0·73	0·79	0·81	0·59	0·67
MnO	0·09	0·10	0·08	0·11	0·09	0·09	0·08	0·08
Total	(100)	(100)	(100)	(100)	(100)	99·61	(100)	—
Fe°	3·67	4·03	3·69	3·48	3·57	3·75	3·70	3·11
S.G.	—	—	—	—	—	—	—	—
Wt. (g)	6·0	10·4	—	2·5	6·5	8·1	5·5	2·7

* By X-ray fluorescence,

the philippinites, australites and moldavites, appear to be in fair agreement with the literature—at least they are not all lower than the literature analyses, and (2) the values obtained for strontium (SCHNETZLER and PINSON, 1964), which has a geochemical coherence to calcium, are distinctly lower in the indochinites than the values obtained for the philippinites. In the conventional method of rock analysis, calcium and magnesium are separated by the precipitation of calcium oxalate and the determination of magnesium is from the filtrate. As 23 of the 24 indochinites from Barnes were analysed by one analyst, it is suggested that consistent incomplete separations may have caused high CaO and correspondingly low MgO results. The methods used in the analyses reported here do not require the separation of calcium and magnesium and the monitoring with G-1 and W-1 suggests that the CaO and MgO determinations were essentially correct. Thus, it is suggested that the CaO and MgO results reported in the literature for the indochinites are in error and the averages reported here should be considered closer to the true average for the group.

Table 3 gives the average values of the indochinites and philippinites, with calculations of the spread of results expressed as standard (σ) and relative (C) deviation of a single analysis. Comparison of the relative deviations with estimates of analytical precision given above indicate that the spread of results in almost all cases are greater than can be expected from analytical error. Total iron and TiO_2 in the philippinites are the possible exceptions. TAYLOR (1962) found the same order of magnitude in the variation of most major constituents of australites.

The first six philippinites (T3959 through T3965) listed in Table 2 are from one site on the island of Luzon—the Santa Mesa site in Rizal Province. The next seven samples (T3379 through T3984) come from another site—the Pugad–Babuy site in Bulakan Province. Both of these sites are near Manila. Therefore the opportunity exists to test if variations occur within small areas, and between two areas which, due to their proximity, might be assumed to have a common origin and/or parent material. The average composition for each site, and the statistical computations, have been calculated from the data in Table 2 and are shown in Table 4. By comparison of the relative deviation (C) values of this table with values estimated for the analytical procedures it appears that many of the constituents have a greater variation than can be accounted for by analytical error. Even if these deviations are compared with the most pessimistic estimates of analytical precision Al_2O_3, MgO, CaO, and Na_2O in the Santa Mesa samples, and CaO, Na_2O, and MnO in the Pugad–Babuy samples exhibit significantly greater variation than just analytical error. Thus the data suggest there are real differences in composition, not only within a given locality such as Indo-China, but also within restricted tektite sites.

The average compositions of the two sites, as listed in Table 4, are quite similar. It is possible to test the degree of similarity by the Null Hypothesis (MORONEY, 1956). According to the Null Hypothesis there is only a 5 per cent probability that the difference between the average of two groups is equal to two standard deviations of the difference if the actual difference between the two groups is zero. MORONEY (1956, p. 220) regards this occurrence as "probably significant" while a difference of three or more standard deviations can be regarded as "definitely significant", the probability being less than one half of one per cent that so great a difference should occur by chance in random sampling of one population. Applying this hypothesis to the data in Table 4 for the two sites in the Philippine Islands it is found that only MnO reaches the "probably significant" level—the difference equalling two standard deviations of the difference. As the probability of this occurring if the actual difference between the groups is zero is approximately one in twenty and as there were ten pairs of constituents tested, it is felt the occurrence of only this much difference in one pair is not significant. Thus the two sites cannot be considered independent on the basis of their chemical composition, although BEYER (1955) states that the samples from the two sites have quite distinct differences in physical appearance.

If the same test is applied to the indochinite and philippinite data of Table 3, it

Table 4. Average compositions of the samples from the Santa Mesa site and the Pugad–Babuy site, P.I.

	Santa Mesa site, P.I. (6)			Pugad–Babuy site, P.I. (7)		
	$\bar{x}$	σ	$C\%$	$\bar{x}$	σ	$C(\%)$
SiO_2	70·7	±1·2	±1·7	70·8	±0·60	±0·8
Al_2O_3	13·88	0·86	6·2	14·02	0·51	3·6
TiO_2	0·80	0·035	4·4	0·79	0·023	2·9
Total Fe as Fe_2O_3	5·54	0·18	3·3	5·44	0·07	1·3
FeO	4·35	0·24	5·5	4·25	0·13	3·2
MgO	2·61	0·15	5·7	2·54	0·09	3·5
CaO	3·17	0·20	6·3	3·17	0·23	7·3
Na_2O	1·40	0·18	12·9	1·39	0·12	8·6
K_2O	2·40	0·10	4·2	2·44	0·10	4·1
MnO	0·88	0·06	6·8	0·98	0·11	11·0

is found that five of the constituents exhibit differences that are definitely significant. The differences in the means of the two groups for SiO_2, Al_2O_3 and TiO_2 equals approximately three standard deviations of the difference, while the difference in strontium values equals 9 standard deviations, and the difference in CaO values equals 15 standard deviations of the difference. The data for the other constituents do not suggest any significant differences in composition.

COHEN (1963b) has stated that there appears to be a relation between composition and size for samples within a given site. He refers specifically to the 6 samples from the Santa Mesa site, the 7 from the Pugad–Babuy site and the 3 from Kouang-Tcheou-wan. The supposed correlation of decreasing silica with increasing sample weight is theorized to be related to differences in ballistic trajectory (and thus temperature) of samples of various masses having the same flight distance. It can be seen from Table 2 that the three Kouang-Tcheou-wan tektites show some correlation between SiO_2 and mass, and that the Santa Mesa samples suggest a correlation. However, considering the analytical precision of the analyses, we feel the Pugad–Babuy samples do not exhibit any discernible correlation and more samples must be analysed before any such correlations could be considered statistically significant.

The data on the southeast Asian tektites presented in this paper do not suggest to us a regional change in composition of the type noted by TAYLOR (1960) in the australites. He found a decrease in alkali element content in 14 australites from west to east, parallel to the decrease in specific gravity reported by BAKER and FORSTER (1943). Over a distance of approximately 1300 miles all the alkali elements exhibited a uniform change of approximately 20 per cent. It is apparent from the data in Tables 2 and 3 that sodium, potassium and rubidium do not show any significant decrease from Indo-China to the Philippine Islands (i.e. west to east), despite the fact that these two localities are approximately 800 miles apart. There also appears to be no uniform change in composition in a north–south direction since the Kouang–Tcheou–wan samples are quite similar in composition to the Dalat samples which lie approximately 650 miles to the south.

Thus the data presented here do not indicate any selective volatilization of elements during passage of the material from west to east (or in any other direction), as suggested by the compositional changes in australites. The two elements which exhibit the greatest difference between the two groups, calcium and strontium, would not be expected to be selectively volatilized without much greater volatilization of many of the other elements, e.g. the alkalis. As LOVERING (1960) points out, it is reasonable to assume that the relative volatilities would correspond to the boiling points of the normal oxides, and the order might be approximately MgO, CaO $< Al_2O_3 < SiO_2$, FeO $< Na_2O$, K_2O. Fusion studies by LOVERING (1960) and FRIEDMAN *et al.* (1960) suggest that this order is essentially correct.

The philippinites and indochinites might be completely independent groups, from completely different source materials; in this case their similarities would be just as difficult to explain. Considering these similarities (i.e. total Fe, MgO, K_2O, Na_2O, MnO) it might be more reasonable to consider the higher calcium and strontium contents of the philippinites due to contamination, by some unknown means, by a high calcium–strontium source—limestone.

Combining the data presented in this paper with previously reported analyses of southest Asian tektites, COHEN (1963b) reaches the conclusion that these tektites represent two strewn fields having a common center of origin. One strewn field incorporates the tektites of Indo-China and Java while the other includes the tektites of Thailand, the South China Islands (Kouang-Tcheou-wan) and the Philippine Islands. He postulates a second, independent, impact to produce the australites. However, the delineation between the two southeast Asian strewn fields is not apparent from the major element analyses. Indeed, we believe the major element analyses reported to date show that tektites from the Australasian area have a unity of composition which is most readily explained by a common source or origin, rather than two as proposed by COHEN.

The moldavites in Table 2 are listed in order of geographic location from west to east. COHEN (1963a) states that the analyses of moldavites in the literature indicate a decrease in silica from west to east, and he interprets this as supporting evidence for the production of tektites by asteroid or comet impact at the Ries Kessel, which lies to the west of the moldavite strewn field. The new data reported in this paper do not clarify any geographic trend in moldavite major element composition. Any trend among the moldavite macroanalyses now available, which have accurate location data—seven from BARNES (1940), four others listed by COHEN (1963a), and the seven new analyses given in this paper—is due to one tektite in the western part of the field (Radomilice, Bohemia) which has 84·5% SiO_2 and one tektite toward the eastern edge (Senorady, Moravia) which has only 74·9% SiO_2. The other 16 moldavites have SiO_2 contents, in seemingly random geographic order, from approximately 77·1% to 82·3%.

Five of the available moldavite analyses are of samples from Radomilice and these samples have rather unusual compositions when compared to the other 13 moldavite analyses. For example, four of the five have distinctly lower K_2O contents than the tektites from the other localities.

TAYLOR *et al.* (1961) pointed out the inverse relationship between SiO_2 and the other major constituents in australites and the positive correlations the other constituents show among themselves. These relationships can be seen in most of the elements in Table 2. The correlation coefficients of the various pairs are not as statistically significant as those reported by TAYLOR, largely because the variations exhibited by indochinites and philippinites are not as great as those in the australites and the analytical errror masks the small variations.

The similarity of the two "amerikanites", 3967 and 3996, to obsidian and dissimilarity to tektites is apparent. In view of the analyses reported by MARTIN and KOOMANS (1955) and those reported here, it is believed these objects are merely stream worn obsidian pebbles and they should not be considered as possible tektites.

SUMMARY

Although the following results of this investigation do not point toward a specific mode of origin for tektites, they add to the limiting factors that must be accounted for in any proposed theory of origin.

1. The philippinites, analysed for the first time in any substantial number during this investigation, have many chemical similarities to the indochinites.

2. However, the philippinites and indochinites analysed here differ significantly in SiO_2, Al_2O_3, TiO_2, CaO and Sr contents, and there is a very high probability that they represent different populations. In particular, the calcium and strontium contents are distinctly lower in the indochinites than in the philippinites, suggesting that the two may have come from the same source, but the philippinite melt was contaminated, by some unknown means, by limestone.

3. The CaO contents of the indochinites analysed in this investigation are distinctly lower and the MgO contents higher, than the analyses in the literature.

4. Real variations, up to approximately 10 per cent for some constituents, exist within the philippinites and indochinites and even within the restricted Santa Mesa and Pugad–Babuy sites of the Philippine Islands, in agreement with the variations found by TAYLOR (1962) for the australites.

5. The two sites in the Philippine Islands do not differ significantly in average chemical composition and are probably parts of the same population.

6. No particular geographic trends are observed in the chemical compositions of the various groups. The new moldavite analyses do not confirm the supposed SiO_2 decrease from west to east as suggested by COHEN (1963a).

7. The similarity in major element composition between the southeast Asian tektites and the australites (TAYLOR, 1962) is striking. This unity of chemical character is strong evidence in itself, exclusive of aerodynamic or age data (CHAPMAN,

the philippinites, australites and moldavites, appear to be in fair agreement with the literature—at least they are not all lower than the literature analyses, and (2) the values obtained for strontium (SCHNETZLER and PINSON, 1964), which has a geochemical coherence to calcium, are distinctly lower in the indochinites than the values obtained for the philippinites. In the conventional method of rock analysis, calcium and magnesium are separated by the precipitation of calcium oxalate and the determination of magnesium is from the filtrate. As 23 of the 24 indochinites from Barnes were analysed by one analyst, it is suggested that consistent incomplete separations may have caused high CaO and correspondingly low MgO results. The methods used in the analyses reported here do not require the separation of calcium and magnesium and the monitoring with G-1 and W-1 suggests that the CaO and MgO determinations were essentially correct. Thus, it is suggested that the CaO and MgO results reported in the literature for the indochinites are in error and the averages reported here should be considered closer to the true average for the group.

Table 3 gives the average values of the indochinites and philippinites, with calculations of the spread of results expressed as standard (σ) and relative (C) deviation of a single analysis. Comparison of the relative deviations with estimates of analytical precision given above indicate that the spread of results in almost all cases are greater than can be expected from analytical error. Total iron and TiO_2 in the philippinites are the possible exceptions. TAYLOR (1962) found the same order of magnitude in the variation of most major constituents of australites.

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1963; ZAHRINGER, 1963), that the australasian tektites had a common origin and represent one large strewn field.

Acknowledgements—This work was supported by the Lunar and Planetary Exploration Branch of the Geophysics Research Directorate, Cambridge Air Force Research Center, Bedford, Massachusetts under Contract No. A.F. 19 (604)-6135, and the National Aeronautics and Space Administration under grant NSG-222-61.

The authors are grateful to the following individuals and organizations who provided samples: CLIFFORD FRONDEL (Harvard University), IRVING FRIEDMAN (U.S.G.S.), K. RANKAMA (Helsinki), ALVIN COHEN (Mellon Institute), G. S. HAWKINS (Boston University), and J. G. LESTER (Emory University).

The assistance of Professor JOHN HOWER in the X-ray fluorescence analyses and Mr. JOHN PHILPOTS in some of the rapid silicate analyses is gratefully acknowledged.

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